The Resistivity of the Liquid Alloys, Mercury-Lead and Lead-Tin.

by

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B I B L I O G R A P H Y

Technologic Papers of the Bureau of Standards, Number 170, 1921, Pyrometric Practice.

Campbell, Modern Electrical Theory.

Desch, C. H., Intermetallic Compounds.

Edser and Griffith, Pyrometric Practice.

Emery, G. V., The Resistivity of Liquid Alloys Thesis, Hg-Sn.

Graetz, Handbuchder Elektrizitat und des Magnetismus, Volume 3.

Ibbotson, Fred, Analysis of Non-Ferrous Alloys.

Kaye, W. W. C. and Laby, T. H., Physical and Chemical Constants, and some Mathematical Functions, Fourth Edition, 1921.

Kent, C. V., The Optical Constants of Liquid Alloys, Physical Review, Volume 14, Number 6, December 1919.

Kraus, C. A., The Properties of Electrically Conducting Systems.

Landolt und Bornstein, Physicalisch-Chemische Tabellen, Third Edition, 1905.

I N T R O D U C T I O N

Metallic alloys may be divided into four classes which exhibit distinct properties. These are: First, solid alloys in which pure crystals of the constituent elements are present in intimate contact; Second, solid alloys in which mixed crystals of the constituent elements are present; Third, solid alloys in which the constituent elements are present; and Fourth, liquid alloys. Among the solid alloys, several of the types often appear in a single alloy. This is the case, for example, when mixed crystals are formed over limited concentration intervals.

We may classify conductors in three ways, according to the way in which electricity is carried along them. In electrolytes the current is carried by dissociated parts, the positive ions going in the direction of the positive current and the negative charge in the opposite direction. These two streams traveling in opposite directions result in a change of concentration of the electrolyte where the current enters and leaves.

In gases a different plan of conduction seems to exist. A free electron moving in the gas, in an electric field, causes other electrons and the gas is soon ionized and becomes conducting while the field exists.

When a metal is changed into the liquid state, its conducting properties change considerably. Its resistivity is generally increased, and its temperature resistance coefficient is very small compared with that in the solid state. Its conductivity is still very large compared to electrolytes, but as no change occurs in the passage of a current, it is classified as a pure conductor. Once in the liquid state, its previous history can have no effect on its conducting properties, and this, along with the fact that exactly similar conditions can be produced, simplifies the study of the conducting properties of liquid metals.

Matthiessen, Stroughal, and Roberts investigated the specific conductance of Au-Ag at ordinary temperatures for various percents concentration. Their conductance curves agree very well. The conductivity curve by Brinell's method shows many interesting changes for the alloy of Ag-Mg for different concentrations in the solid state. The conduc-

tivity curves of many other alloys show various changes, especially as the temperature of the solid is raised to the liquid state. The curves become simpler in form suggesting a simpler form in the liquid state, which has been found true for most alloys.

The resistivity has been determined for many alloys, more having been done on the solid alloys than the liquid. A few optical constants have been determined by Bournelli. He worked with the binary mixtures of Ag-Fe, Ag-Sn, Cd-Hg, Cu-Sn, Cu-Zn, and Cu-Ni, in each case only a portion of the latter component was present. Littleton made a systematic study of Fe-Ni, Ni-Si, Fe-Mn, Al-Cu, Cu-Ni, and Fe-Cu alloys. His efforts were chiefly directed to tracing the effects of the presence of alloys of Bi-Pb, Cd-Pb, and Sn-Pb, and determining their optical constants.

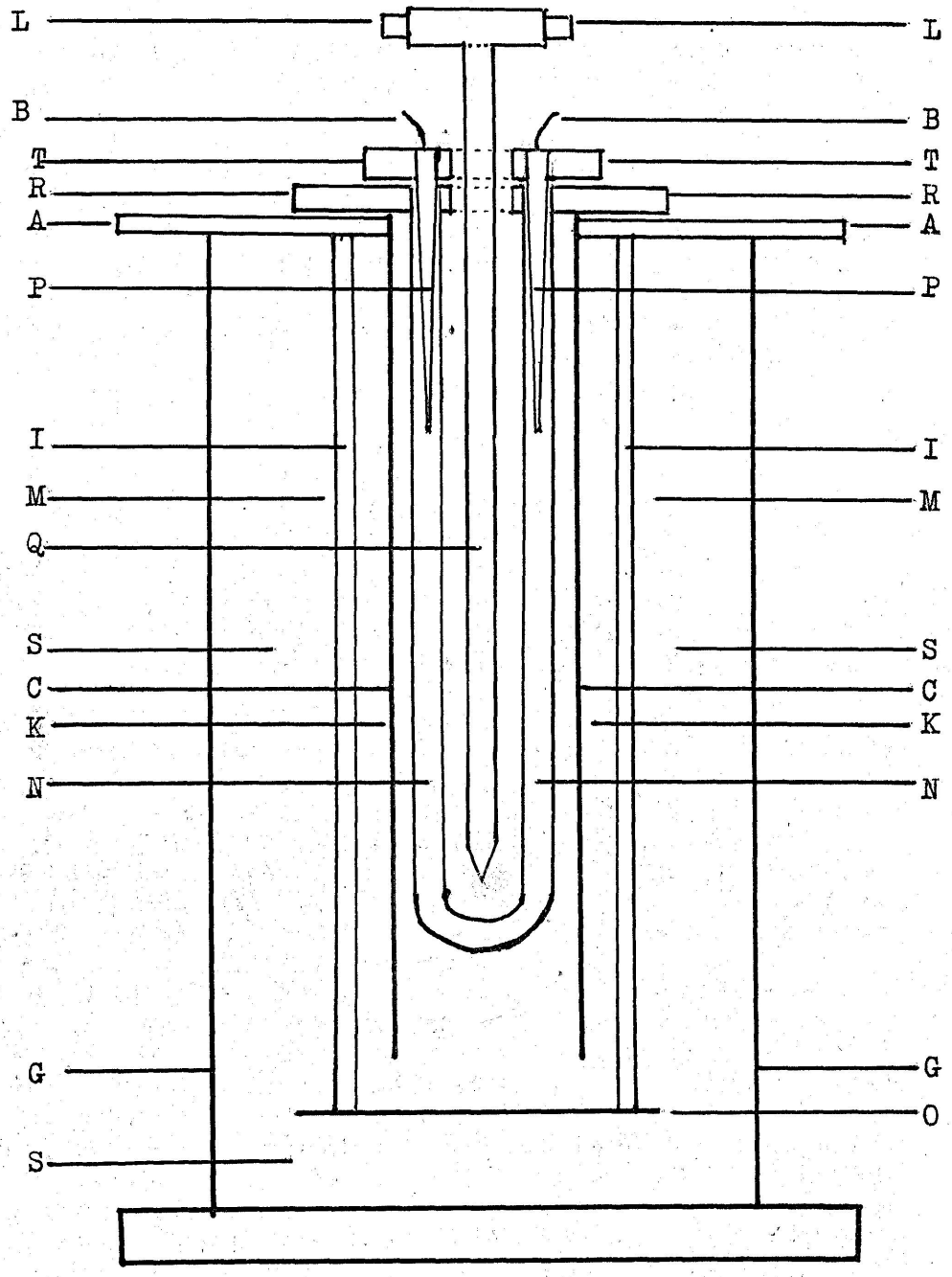
The actual measurement of the resistivity of liquid alloys has been rather limited for the higher temperatures. Weber worked with the liquids alloys, Hg-Cd, Hg-Sn, Hg-Pb, and Hg-Bi. His work was merely qualitative, due to insufficient methods and apparatus.

The resistivity of a liquid alloy seems to be consistent with the free electron theory. This follows from the Optical Data of C. V. Kent, that the number of free electrons and the frequency of the electron impact both vary linearly with the atomic concentration in the alloys investigated in which no compounds are formed.

George V. Emery worked with the liquid alloy of Hg-Sn and found that the data obtained is consistent with the electron theory of resistance developed by Drude, with the exception of his assumptions as to temperature.

The object of my work on the liquid alloys of Hg-Pb and Pb-Sn is (a) To obtain more accurate data on the alloys rich in Pb than has been established. Weber seems to have done the only work on these liquid alloys and his results are apparently uncertain. (b) To measure the resistance at enough points to get resistance-temperature curves from which we may get data for ploting resistance-concentration curves for different temperatures. (c) To test the resistance-concentration curves for certain relations involved in the electron theory of the conduction of liquid alloys.

The Furnace.



DESCRIPTION OF APPARATUS AND METHODS

General Method

The alloy of known concentration is heated in a U-tube in an electric furnace whose temperature is controled by a thermostat. Its temperature is measured by a Kelvin bridge method at several different temperatures measured by a platinum resistance thermometer.

From the resistance temperature curves thus obtained at known atomic concentrations, curves showing the variation of resistance with atomic concentration at constant temperature can be drawn. The shapes of these will then perhaps give some indication of the possible conditions of the so called "free electrons" in liquid alloys.

The Furnace

The furnace proper is fixed in a sheet iron can C, and loosely insulated with asbestos packing, S. The cover, A, is a piece of transite about a quarter of an inch thick and nine inches square. It contains a hole in the center just large enough to allow the tube containing the alloy to pass through.

The heating element, C and K, consists of a malleable iron pipe, C, about two inches in diameter and fourteen inches long. This is wrapped with a single layer of number eighteen nichrome wire, K, which is insulated from the pipe with sheet asbestos. This wire leads to the terminals where alternating current is applied. This sets up induced currents in the iron which causes more regular heating. Stray currents are cut qut when the alternating current is used instead of the direct current. If direct current is used trouble may be experienced by certain effects on the wiring which causes shifting of the 0 readings on the ballastic galvanometers. When alternating current is used the effect would be changing the direction so often that the effects on the galvanometers will not be noticed. The element was capable of producing a temperature of 600° C. How much more might be produced is not known as the temperature of 600° C was the highest required in this work. The heating was done by 110 volts alternating current and the current used was about 3 amperes. For temperatures from 400° C to 550° C the current reading was about 4 amperes for initial heating.

The copper tube, C, whose cross-section is the same shape and size of the opening in the transite which is rectangular in shape with circular ends, and of the dimensions one-half inch by one and one-half inches, is fixed securely to the transite just beneath the hole. The tube is about twelve inches long and does not go through the transite. This serves to distribute the heat more evenly along the tube containing the alloy. This tube is also wrapped with a layer of nickel wire insulated from the copper with a layer of sheet asbestos. This nickel coil, the ends of which terminated at the terminals of a wheatstone bridge forming one of the arms is for the temperature control apparatus or thermostat which will be explained latter. A change in the temperature caused a change in the resistance of the nickel wire great enough so that the temperature could be kept constant to a tenth of a degree change in ten minutes without any difficulty. This was not found necessary however as the temperature and resistance measurements could be made in much shorter time after the temperature had become constant. By applying the full current used for the heating, the constant temperature could be reached and a reading taken within twenty to thirty minutes. After the first reading was obtained the time to heat the furnace to about 300° C is thirty minutes. It takes about twenty to thirty minutes to raise the temperature 40° and get it constant. This makes a reading of resistance and temperature every thirty minutes after the furnace is heated and the first reading obtained. This time varies some as the temperatures become higher. This rapidity of taking readings and with such ease is due to the thermostat.

The container for the alloy was a U shaped pyrex tube about twenty-two inches long. The pyrex was used on account of its high melting point of about 720° C and its ability to stand quick changes in temperature. The distance between the parallel tubes was about one inch. The bore of the tube was about four millimeters, making a very convenient tube to handle. The ends of the tube were clamped in a piece of transite about a quarter of an inch thick and one by one and one-half inches in size, which after the holes had been bored correctly for the tubes and the thermometer which went through the center, was sawed lengthwise through the center. The ends of the tubes were brought just flush with the clamp. The tube is shown on the figure by T and the clamp by R. The clamp served two purposes; to hold the tube and to make a permanent base for the potential leads which were clamped in a similar

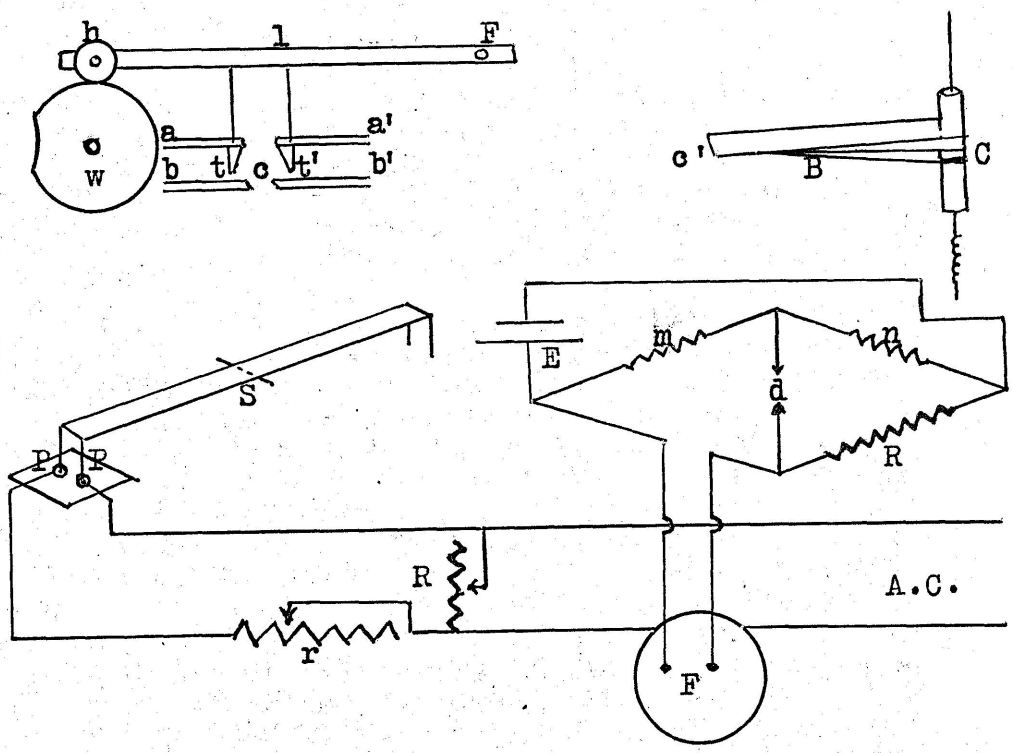
clamp. By this method of mounting the pieces, a constant length of the alloy was used at all times without any measurable error. The tubes clamped in the potential clamp, T, were drawn from pyrex glass of small bore and were quite stout. They reached down the U tube about three inches. The bridge connections to the alloy were of considerable importance. In order to avoid possible contamination of the alloy by the leads, the current leads were of iron as they would not amalgamate. The potential leads however had to satisfy two conditions; they must first be of such a material that will not dissolve in the alloy and contaminate it and second, they must be of such a material that will make a contact with the alloy with the least possible resistance.

The temperature was taken with a resistance thermometer, the coil of which was set well in the center of the column of alloy whose resistance was measured. The thermometer is shown as Q with the terminals for the leads to the bridge as L. The potential leads are shown as B. The thermometer was always set at the same depth and was held by a special clamp made for that purpose.

The Thermostat.

The purpose of the thermostat as mentioned in the discussion of the furnace was to hold the temperature of the furnace constant so that readings of the temperature and the resistance could be taken at the same time when the alloy was at the same temperature as that read from the thermometer. The general principal of the thermostat is the mechanical opening or closing of a switch which causes more ore less current to flow through the heating coil of the furnace. It saves much time as the temperature can be run up quickly and stopped at the desired point. Another advantage is that the wheatstone bridge may be set at some value of resistance and the apparatus left to itself for any desired time, as the temperature will reach this value and stay there. In previous work the time required for obtaining a sufficiently steady temperature to make readings was from three to four hours but in this apparatus a reading may be obtained within thirty to forty minutes after the furnace has been once heated up, which may take thirty minutes. The workings of the thermostat may best be shown from the construction.

The Thermostat.

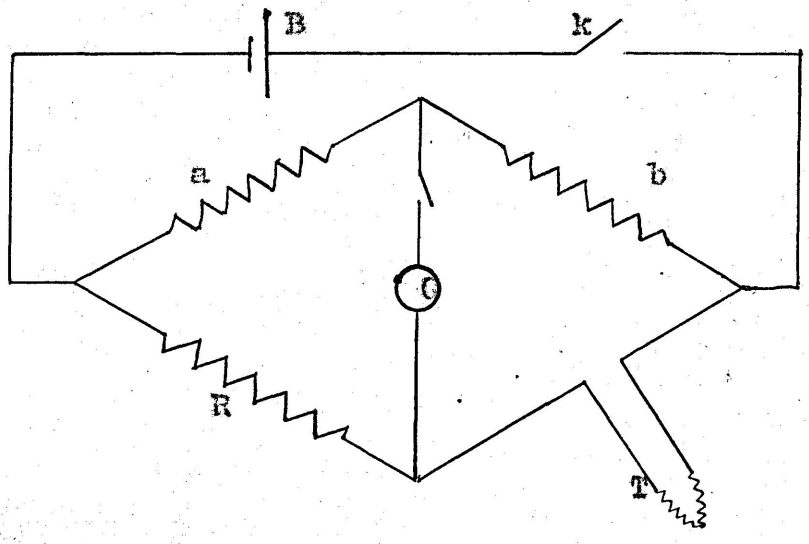


The thermostat consists of the arm l fastened at F and the other end with the roller h rides a motor driven cam w which makes a revolution in about a minute. When the roller h reaches the depression in the cam the contact points a and b and a' and b' come in contact closing the circuits ab and a'b'. The contact pieces a and a' are fastened directly to the arm l. The other two, b and b', are attached to the arm by cords that run under a pulley that is below the contacts thus as the upper pieces are pulled up the lower ones are drawn down. This keeps the coil of the galvonometer from shaking too violently when the boom is released, also giving more room for the boom to swing. In each of these circuits, ab, and a'b', there is an electromagnet and battery connected in series. The electromagnets are arranged so that one is on each side of the axle of the switch S. When one set of the points at c are closed and the other open, the switch S will be thrown one way and if the other set of points are closed and these left open, the switch will be thrown the other way. The coil C is that of a swinging coil galvanometer and the galvanometer sets so that the end of the boom B fits in between the points at c, the boom B being perpendicular to the plane of the points. The boom is a thin piece of glased paper cut into the shape of an isosceles trapezoid about 3/8 x 1 1/4 x 5 inches. The edges were bent at right angles to plane making the total width about 3/8 of an inch. The wider end is glued to the movable coil of a ballistic galvanometer. The flap which will be the narrow end fits between the points at C, insulating a pair according to which way the boom swings. The height of the coil is adjusted so that the flap c' will swing in the contact points at t and t'. The galvanometer is connected across the circuit shown at d. Since the nickel coil in the furnace is not of very high resistance, the ratio arms of the bridge are adjusted so that a large resistance is taken out of R. This fixes it so that the galvanometer will swing with a slight change in the resistance of the nickel coil in the furnace. The adjustment arm of the bridge is calibrated for several temperatures and a curve constructed so that an approximation to the temperature sought may be obtained. When the bridge has been set for a higher temperature the arms are unbalanced and the boom B swings to one side closing one set of the points at c. This causes the switch to swing over, closing the circuit at P, as the switch S is of iron. This throws a shunt across the resistance R causing more current to flow through the furnace F. When the temperature of the furnace has become such that the resistance of the nickel coil makes a balance accross the arms of the bridge and goes on the other side a fraction of an ohm, the boom B swings to the other set of points insulating them and letting the

former set close. The switch S then opens and the current in the furnace is lessened. After the switch S has been thrown back for heating which may take as much as ten minutes, the temperature and resistance readings may soon be taken. The resistance in r is usually reduced to that required to keep the current through the furnace a little higher than that necessary for the heating. By this method a steady reading may be had for as long as five or ten minutes. It will be noticed that in this thermostat that the current flows through the electromagnets only the short interval that the roller h is in depression.

An alloy that had once been run was tried without the thermostat to test the advantage of its presence. It was found that much more time was needed for the reaching of a temperature steady enough to be read. It took about four to five Hours to get four points for a curve and they would not fall on a straight line as they should from former experience and none of the points could be repeated, showing that the readings were not consistent. The same alloy was then tried with the aid of the thermostat. The new points Öbtained in about two hours fell on a straight line and close to the same line what was obtained in the first run. This shows that the results obtained with the thermostat are consistant.

The Thermometer



The temperature of the alloy was taken with a resistance thermometer of German make. It was a two lead type and of a resistance of about sixty ohms. The thermometer proper was about twelve inches long. The platinum coil that was in the lower part was of fine wire and the coil was about four inches long. The leads were of large gold wire that led to the terminals at the top of the thermometer. This was all inside of a quartz tube that was fairly thin and took on the surrounding temperature readily. It was found that on putting the thermometer in the heated furnace it took the same temperature quickly.

An Elliott Brothers box was used as the bridge. The resistance of the arms was made such that the resistance out of R was fifty times that of the thermometer. A constant ratio was kept in the arms throughout the measurements. The R out of the box for most of the temperatures was usually above and below the six thousand mark. This would make the resistance of the thermometer one hundred and twenty ohms. It was seen that since the coil was of such high resistance compared with the short leads of large gold wire that the change in their resistance would be negligible.

Calibration of Thermometer

The resistance of the platinum coil of the thermometer was determined for four well known points. The first was that of melting ice. The same was tried in melting snow and the results checked. The next point was the steam point. This was repeated and checked well. The third point was the point of boiling napthalene. This temperature was around 217° C. The fourth and the highest point taken was that of boiling sulphur. This was the most difficult one to check. The sulphur had to be boiled just right to get the true vapor. After several trials at the boiling point the point could be checked. The method used for getting the sulphur point was about the same as that outlined in Pyrometric Practice as was given in Edser and Griffith. There was about thirty grams of pure sulphur put in a pyrex tube about one and one-half inches in diameter and about nine inches long. It was well wrapped with asbestos so as to eliminate radiation. The tube was then placed on an electric furnace into which the tube just fitted and was heated slowly. After the sulphur began to boil the furnace was regulated until the sulphur boiled. This was kept up until the vapor which condensed on the top of the tube ran freely down the sides of the tube. The tube was covered so that very little of the fumes could escape. By this method and with the outline just mentioned, the point was easily checked within 15° C. The barometric

readings were taken before and after the resistance readings. From Kaye and Laby's Chemical and Physical constants, and from the Technologic Papers of the Bureau of Standards, the correct temperatures for the resistances were determined.

By the use of Callendar's Difference formula for the changing platinum thermometer readings to the gas scale, namely

$$t - pt = d\,(t/100 - 1)\,t/100$$

in which t is the gas thermometer temperature, d a constant, approximately 1.5 for pure platinum, pt, the platinum temperature is obtained from the relation

$$pt = 100\,\frac{R_t - R_0}{R_1 - R_0}$$

in which R_0 is the ice resistance, R_1 the steam resistance, and R_t any other resistance for which pt is to be determined.

From these two formulas the pt being determined from the last, the constant of the thermometer, d, is determined. Then by substituting the values of the pt that are calculated from the formula in the first formula with the constant found, we get a series of values that can be plotted. We get a temperature resistance curve that gives any temperature from 0° to 600° C. The temperature may be read from the curve with an accuracy of one-tenth of a degree and the resistance can be read to a hundredth of an ohm. It was necessary to have the resistance scale on the curve reading finer than the temperature as the temperature of about 5° C corresponds to one ohm change in the resistance of the thermometer.

After these curves were plotted it was found that the resistance found for the napthaline point by the curve checked with that obtained by experiment by a part of a degree. This point was not plotted with the regular points and was independent of the other points.

The steam, ice, and sulphur points were rechecked far in the work and found to differ inappreciably from the former readings with which the calibration curve was plotted.

The Fixed Points For The Calibration Curve

Mean Readings:

Resistance Out Of Arm R Of Wheatstone Bridge	Resistance Of Thermometer Coil	Barometric Readings
	In Snow.	
2504	50.08	73.90
	In Ice.	
25035	50.07	73.92
	In Steam.	
3454	69.08	73.98

Boiling point from tables = 99.255° C.

	Napthalene Point	
4546	90.92	73.97

Boiling point of napthalene =
217.9° + .058 (aP - 760) = 216.68° C.
aP is the barometric pressure in mm.Hg.

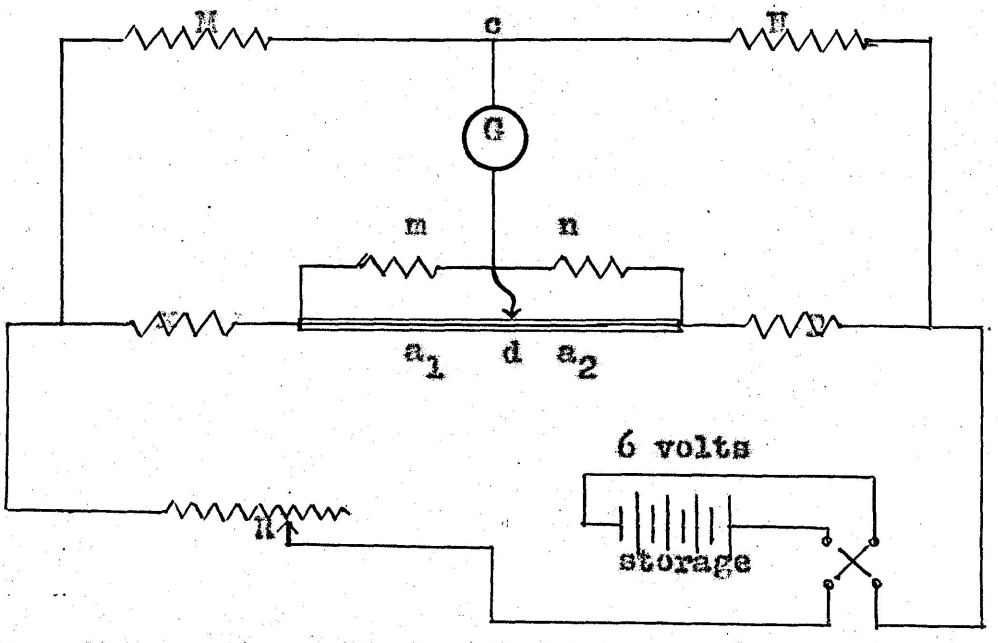
	Sulphur Point	
6514	130.28	73.58

Boiling point of sulphur =
444.6° + .091 (aP - 760) = 442.4° C.

Tables from Pyrometric Practice, Bureau of Standards.

RESISTANCE MEASUREMENT OF THE ALLOY

The Kelvin Bridge is used to determine the low resistance of the alloy. The bridge may be placed some distance from the resistance to be measured. The resistance in series with the contacts or potential leads is quite high, making a little contact resistance negligible. The usual type of the bridge has the standard bar along which a slider is used to determine the low resistance as the bar is of very low resistance itself. The bridge used here is of the same type but it is changed by fastening the slider d permanently to the bar by soldering. Two accurate boxes are then inserted in the potential leads, that is in series with M and m. The boxes used here are a couple of four dial Leeds and Northrup which are tested with a Leeds and Northrup four dial bridge and all three found to agree. The boxes were new and had not been used in any other work. By making the ratios on the bridge equal, and



since the reading of both the boxes are the same, we have as our reading the resistance in one of the boxes in the potential leads plus the resistance in that side of the ratio divided by the resistance of the other ratio. The rheostat R is set so that there is enough current flowing through the bridge to cause a deflection of one centimeter on the scale for one ohm change in the resistance in the potential leads. This gives us a reading of five numbers. Since the resistance on each side of the ratio is one thousand ohms and the resistance of the portion of the bar used is .01 of an

ohm, we read the resistance as, for example, .015643, the first four numbers being from the resistances and the last from the estimated galvanometer deflection.

From the diagram and the discussion given we may deduce the theory of the bridge as shown. The arms of the bridge are

$$M, \quad N, \quad x + \frac{m a_1}{m + a_1}, \text{ and } p + \frac{n a_2}{n + a_2}$$

With the bridge balanced we may assume some point d on the heavy conductor $a_1 a_2$ to be at the same potential as c, and that

$$M : N :: x + \frac{m a_1}{m + a_1} : p + \frac{n a_2}{n + a_2}$$

As c and d are the same potential,

$$m/a_1 = n/a_2 , \quad \text{or} \quad \frac{m}{m + a_1} = \frac{n}{n + a_2}$$

Substituting $\frac{n}{n + a_2}$ for its equal, $\frac{m}{m + a_1}$ we have

$$M/N = \frac{x + \left(\frac{m}{m + a_1}\right) a_1}{p + \left(\frac{m}{m + a_1}\right) a_2}$$

Or

$$x = M/N \left(p + \frac{m}{m + a_1} a_2\right) - \frac{m}{m + a_1} a_1$$

$$= Mp/N - \frac{m a_2}{m + a_1} (M/N - a_1/a_2).$$

Substituting m/n for its equal a_1/a_2.

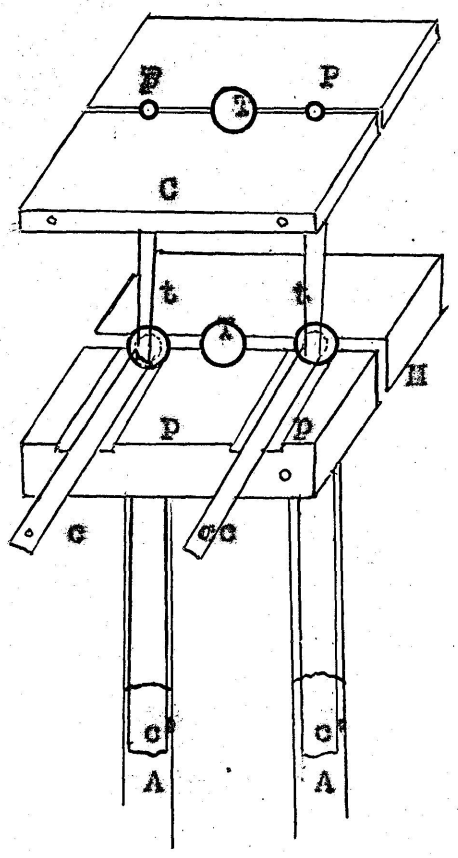
$$x = pM/N + \frac{m a_2}{m + a_1} (M/N - m/n).$$

If therefore the ratio of M/N and m/n is the same, the second term vanishes and

$$x = \frac{M}{N} p.$$

Keeping the values of M,N,m,n, relatively large, the resistance of their external connections make no appreciable error, while the current leads to the low resistances, p and x, lie entirely outside the points between which the resistances are measured.

The construction of the bridge connections required considerable skill as they are of considerable importance. The current leads cc are of small iron tubes that reach down into the tube of alloy about two and one-half inches. The part that is out of the tube is a strap of the tube that falls in a groove cut in the tube clamp M. This leaves a smooth flat surface for the clamp that holds the tubes containing the potential leads. The clamp holds a couple of small glass tubes that will go down in the tube containing the alloy and about half an inch farther than the end of the current leads. This clamp rests squarely on the clamp that holds the tube containing the alloy and is held here by two spring clamps that are fastened to the top of the furnace. Since the tubes cannot move out of their positions, there is no chance for the change of the ends of the potential leads. The potential leads just come to the ends of the glass tubes. The alloy usually runs up in the tubes a ways making it unnecessary for the leads to go quite to the end. The potential leads or wires must not be pushed beyond the end of these tubes as this will change the length of the column of mercury whose resistance is to be measured.



The choice of the right electrodes for the potential leads is another very important item. In the run on lead-mercury alloy, platinum was tried for the electrodes. They were welded to the copper wires that lead from the bridge. When a temperature of about 350° C was reached the platinum disappeared, so something must be used besides the platinum. Steel wire was tried but consistant results seemed impossible with it.

Chromel wire was tried but it proved unsatisfactory as it would oxidize causing high contact resistances. When there was any contact resistance, the galvanometer would make a few large deflections and remain to one side of the scale. The chromel was then replaced with some soft iron wires that had been thinly tinned. These were found to work well and were used throughout the work. At the higher concentrations of the mercury which involved higher temperatures also, new electrodes were used for every alloy as the tin would oxidize to some extent when the electrodes were pulled out of the alloy. The current leads were of iron tubes which fitted in the pyrex tube and were found to give no trouble at all. The potential leads went inside the iron tubes and reached a little farther down in the alloy than the current leads.

The iron potential lead electrodes used were about fourteen inches long. They reached from a vacuum cup fastened close by the furnace to the tips of the small pyrex tubes which were set in place as mentioned. These electrodes were connected to the main copper leads from the bridge by means of separate mercury cups which were dipping in water that was in the vacuum cup. This served to keep the two junctions at the same temperature at all times therefore preventing any thermo-electric force.

A reversing switch was used in the battery circuit of the Kelvin bridge. If the galvanometer is balanced using the current in one direction, and is still balanced when the current is reversed, the bridge is balanced, and the resistance and temperature are read. If the zero reading shifts in one direction and after the current is reversed it shifts in the same direction, a thermo-electric force is present. Nothing of this sort was found.

PREPARATION OF THE ALLOY

The preparation of the alloy is very important in that it must be thoroughly mixed and in such a way that an inappreciable amount of it is lost by oxidation. In the mercury-lead alloy, the mercury and lead were the purest obtainable from the chemistry stock room where it is used in analytical work. The lead was received in the granulated form which was melted under oil and put in the form of sheet. The amount that was required to make a certain percent alloy by weight was weighed on the analytical balances which weighed to tenths of a milli-gram. The lead was put in a small pyrex beaker with some parafin wax and set on an electric furnace to heating. The required amount of mercury was weighed and added to the lead which had begun to melt. At very high concentrations of lead a small portion of the weighed lead was mixed with the weighed mercury and more lead added until the total amount was dissolved. The alloy was at all times kept under the melted parafin and the beaker kept covered most of the time to prevent oxidation of the alloy. After the alloy had completely mixed it was poured into the furnace where the tube that was to contain the alloy had been heated to the approximate temperature of the alloy. No trouble was had with the breaking of the pyrex tube. The same tube was used throughout the work. Some of the oil was removed from the alloy as there was an excess. This oil probably got in the tube with the alloy but was easily removed by running an iron wire down in the arms of the tube. After the temperature was quite high for the alloy this was done until there were no air bubbles or oil bubbles in the arms. The surface of the alloy in each arm was covered with parafin oil.

Each concentration of the mercury-lead alloy was determined by chemical analysis. The components of the lower concentrations checked well with the values obtained by weight but the higher ones did not do so well. The mercury seemed to be less with the higher concentration of lead by analysis than was calculated by weight each time. This wasnot due to oxidation but as the alloy was from 300° C to 400° C some of the mercury must have passed off. The change in the concentration during the run of alloy was so little that no change could be detected in the temperature-resistance curves. The maximum change found was about three-fourths of one percent in the mercury. In the high concentrations of lead, the funnel, which fits in one arm of the alloy, and the beaker had to be heated as the alloy was poured into the tube. The alloy hardened in the beaker before it could be poured into the tube without the flame.

The work on the tin-lead was carried on in the same way as the mercury-lead alloy except that the lead was entirely melted and the weighed amount of the tin was slowly added to it. It was thoroughly stirred and mixed before pouring into the tube. The flame at the furnace was used throughout the work on the tin-lead, as the alloy would harden quickly. The potential leads used for the tin-lead were of soft iron wire which tinned readily, therefore giving no contact trouble at the leads. The tin used was obtained from the chemistry stock room and was found to be quite pure. It is used in analytical work. A chemical analysis was run on the lead and on the tin. They were found to be 98 and 98.5% pure respectively. Great care was taken that there were no air or oil bubbles in the arms of the tube with the alloy.

Analysis of Alloys Methods

The process consisted of dissolving a weighed amount of the alloy in concentrated HNO_3. This solution was boiled until clear. It was titrated with a standard solution of KCNS. The solution of KCNS was standardized against pure Hg, and 1 cc was found to be equivalent to .0122 grams of Hg. The end point was found by means of a neutral solution iron alum as outside indicator and was reached when a drop of solution gave a light orange color to a drop of the indicator on a spot plate. The analysis was accurate to .1% and a complete analysis of a sample could be made in about fifteen minutes. The lead was taken out in the sulphate method.

Procedure

The procedure that was followed ran in the following manner. The main switch was closed and the rheostat R set until the ammeter read about four amperes. A mercury thermometer was generally used to get the approximate temperature of the furnace that was to be used for the first reading. When this temperature was reached the resistance R in the bridge was then adjusted until the switch of thermostat would just fly open. The apparatus was left and the alloy prepared. The U tube that was to contain the alloy was put in place in the furnace at the same time that the heating was started. The amount of mercury and lead were weighed out separately for the percentage concentration to be investigated and put in a pyrex beaker with some parafin wax and heated until the two were thoroughly mixed by stiring. The parafin was sufficient in amount to cover the surface of the alloy well. The temperature of the alloy was made about that of the furnace and after most of the oil was removed, it war poured into the U tube.

The tube was filled within an inch of the top. A small piece of parafin was put in each arm of the tube. An iron wire was run down in each arm of the tube several times to remove any air or oil bubbles that might be in the mixture. The tube was examined carefully each time to see that all the air bubbles and oil bubbles were absent. The current and potential electrodes were then put securely in place and clamped. The resistance thermometer was set in place and after a few minutes the resistances in the arms of the temperature and resistance bridges were adjusted until neither galvanometer showed an appreciable deflection. After a few minutes more the deflections were not much different and the balances were made and when neither galvanometer showed any deflection this was taken as the balance and the readings of the resistances were taken. The temperature was taken from the calibration curve and the temperature-resistance curve plotted. If there was any doubt about a point, the alloy was run again without much trouble. For the next point above the first one, the resistance in the arm R of the thermostat was raised enough to change the temperature about 40 or 50°. It was found that about one hundred ohms would do this. Usually four or five points were obtained for each curve. About two grams of the alloy were weighed out on the analytical balances and dissolved in the strong nitric acid. Portions of this were taken and titrated, the average of the titrations was taken for the estimation of the mercury.

Accuracy

The accuracy in this work was probably limited by the apparatus used. The resistance of the temperature bridge box arm was around six thousand ohms. The deflection of the galvanometer was quite sensitive to a change of one ohm in this arm thus the sensitivity was about one part in six thousand. The resistance of the alloy was measured to three-tenths of an ohm and the ohms out of the boxes was around 15500 the last figure being estimated from the galvanometer deflection. It is seen that the accuracy was close to four parts in 15500 or one part in about four thousand. The resistances were not much more accurate than one part in two thousand making the accuracy one part in about two thousand.

The temperature for plotting the curves was read from the calibration curve used to .1° C. The resistances plotted on the graph of the temperature-resistance curves involved the first four figures, the last being estimated.

Apparatus Used

Temperature Measurement:

Elliott Brothers Resistance Box of about 14,000 ohms. This box could be arranged for a wheatstone bridge.

Leeds and Northrup Ballistic Galvanometer serial number 39403.

Resistance Measurement:

Leeds and Northrup type Kelvin Bridge.

Two Four Dial Leeds and Northrup Resistance Boxes

Leeds and Northrup Galvanometer, serial number 39360.

EXPERIMENTAL DATA

Mercury and Lead Alloy
Percent Lead in Alloy of Mercury Lead

Composition % Weight	Composition % Atomic	Resistance Ohms	Temperature ° C	Kelvin	Bridge Alloy Resistance
0	0	89.34	208.0		.021570
		94.94	239.8		.022320
		101.12	274.4		.023220
		105.74	300.4		.023905
		114.64	351.0		.025181
0.934	0.906	96.04	245.6		.020853
		88.26	202.6		.019918
		111.28	326.0		.022663
		117.14	365.3		.023611
2.000	1.925	103.94	290.0		.020542
		94.06	235.0		.019460
		88.00	201.2		.018861
		113.96	347.0		.021601
		116.02	359.0		.021859
		99.60	265.2		.019961
3.100	2.996	92.74	227.8		.018452
		108.04	313.2		.019863
		117.02	364.5		.020827
		102.62	282.5		.019320
4.150	4.014	87.88	200.6		.017605
		103.18	285.6		.018847
		104.18	294.8		.018983
		108.48	315.8		.019312
		115.48	355.8		.019950
4.710	4.550	95.08	240.4		.017858
		103.98	290.1		.018583
		108.18	314.0		.018944
		112.74	340.0		.019345
6.700	6.490	96.94	251.0		.017251
		103.64	288.0		.017753
		110.18	325.0		.018258
		111.18	331.0		.018284

8.10	7.85	92.39	225.8	.016603
		92.98	229.0	.016621
		106.06	296.2	.017474
		107.06	307.6	.017592
		115.46	355.5	.018182
		116.46	361.5	.018242
12.10	11.74	102.66	282.5	.01651
		107.34	309.4	.01678
		109.16	319.4	.01690
		113.58	344.8	.01716
		118.22	371.6	.01748
20.00	19.45	100.60	271.0	.01572
		108.20	314.0	.01609
		115.46	355.5	.01647
		100.60	271.0	.01571
		95.40	242.0	.01546
24.9	24.26	107.20	308.4	.015932
		107.48	310.0	.015942
		103.76	289.0	.015753
		113.28	343.0	.016221
28.9	28.49	105.82	300.6	.015931
		114.74	351.4	.016337
		117.62	368.2	.016478
		95.02	240.2	.015421
34.97	34.20	91.04	218.2	.015408
		104.60	293.6	.015950
		110.40	327.0	.016138
		114.42	349.5	.016291
50.00	49.13	87.80	200.0	.015831
		98.22	258.1	.016219
		108.38	315.1	.016592
		117.38	366.5	.016923
		118.88	375.5	.017012
60.00	59.18	93.14	230.0	.016532
		98.86	261.4	.016744
		106.20	302.1	.017011
		111.44	332.5	.017193
		118.70	374.4	.017502

67.5	66.71	105.50	299.0	.017304
		114.04	347.4	.017610
		118.64	374.0	.017784
		119.54	379.5	.017873
75.0	74.40	105.88	301.0	.017552
		110.56	328.1	.017763
		114.60	350.0	.017952
		117.28	366.2	.018776
80.2	79.65	117.30	366.0	.018253
		127.10	423.6	.018742
		123.04	399.6	.018463
		105.84	300.5	.017715
85.0	84.50	118.36	372.4	.018352
		122.20	395.0	.018532
		130.80	445.5	.019121
		112.65	340.0	.018044
88.0	87.70	134.10	465.0	.019107
		127.48	426.0	.018811
		119.70	380.0	.018442
		107.90	312.0	.017898
88.5	88.10	114.66	351.0	.018213
		109.86	323.6	.018040
		106.70	305.8	.017887
		118.90	375.8	.018379
91.9	91.60	122.90	399.0	.018880
		119.29	377.8	.018658
		115.56	356.3	.018431
		110.52	327.5	.018143
95.0	94.80	136.20	477.0	.019521
		128.80	433.8	.019057
		120.30	384.0	.018523
		114.16	348.0	.018122
97.8	97.70	112.36	337.8	.017861
		123.02	399.5	.018532
		143.42	519.0	.019751
		124.32	407.3	.018545
		110.72	328.5	.017725
100.0	100.00	126.28	418.8	.018621
		132.68	456.6	.018962
		136.88	482.8	.019271
		140.52	504.2	.019470
		127.98	428.8	.018760
		146.34	539.6	.019823

Conductivity of Alloy at 300° and 350° C.

Referred to pure mercury.

% Pb. Atomic	Conductivity	300.00	350.
0.000		1.0000	1.0000
0.906		1.0826	1.0861
2.000		1.1527	1.1609
2.996		1.2140	1.2250
4.014		1.2518	1.2660
4.550		1.2747	1.2910
6.490		1.3333	1.3533
7.850		1.3650	1.3880
11.740		1.4320	1.4610
19.450		1.4933	1.5325
24.260		1.5067	1.5420
28.490		1.5000	1.5412
34.200		1.4970	1.5410
49.130		1.4403	1.4946
59.180		1.4056	1.4543
66.710		1.3800	1.4273
74.400		1.3605	1.4010
79.650		1.3533	1.3910
84.500		1.3486	1.3836
87.700		1.0000	
88.100			
91.600		1.3380	1.3693
94.800		1.3545	1.3869
97.700		1.3696	1.4006
100.000		1.3806	1.4103

Composition Pb. in Alloy % Atomic	R_{300} x 10-3	$\frac{R_o - R_e}{e}$ x 10^{-2}	R_{350} x 10^{-3}	$\frac{R_o - R_e}{e}$ x 10^{-2}	R_{200} x 10^{-3}	$\frac{R_o - R_e}{e}$ x 10^{-2}
0.000	23.88		25.16		21.32	
0.906	22.06		23.16	22.20	19.68	15.80
1.925	20.72		21.67	18.15	18.83	12.93
2.996	19.67		29.54	15.45	17.98	11.20
4.014	19.08		19.86	13.35	17.52	9.43
4.550	18.74		19.49	12.50	17.24	8.97
6.490	17.91		18.59	10.10	16.57	7.32
7.850	17.50		18.12	8.965	16.30	6.39
11.740	16.68		17.22	6.76	15.62	4.91
19.450	15.98		16.42	4.40	15.10	3.21
24.260	15.85		16.28	3.66	15.00	2.65
28.490	15.92		16.32	3.10	15.11	2.18
34.200	15.95		16.29	2.60	15.28	1.24
49.130	16.48		16.83	1.70	15.80	
59.180	16.99		17.33			
66.710	17.31		17.63			
74.400	17.55		17.95			
79.650	17.65		18.09			
84.500	17.71		18.18			
87.700						
88.100						
91.600	17.85		18.37			
94.800	17.63		18.14			
97.700	17.44		17.96			
100.000	17.30		17.84			
27.500			16.00	3.33		

DRUDES THEORY OF CONDUCTION

The current carriers are considered to be free electrons of charge e and mass m moving with a mean velocity v in inter-atomic spaces. Their drift in the direction of the field E constitutes the current. This drift velocity is very small, however, and is assumed negligible in comparison with v. The average time between impacts of a free electron and an atom is t.

Under a field E the electrons are accelerated with a force Ee and their acceleration between the impacts is,

$$a = \frac{\text{force}}{\text{mass}} = \frac{Ee}{m}$$

The velocity required in the time t then is,

$$u = at = (Ee/m)t,$$

And the average drift velocity is,

$$u = 1/2\ u = \frac{Ee}{2m}\ t.$$

This drift velocity is supposed on the average to be lost on each impact.

With N free electrons per centimeter cube the current density is the total quantity per centimeter times its mean velocity or

$$Neu = Ne\ \frac{Ee}{2m}\ t = \frac{ne^2Et}{2m}$$

If we let R represent the resistivity of the conductor and i the current density,

$$R = E/i = \frac{E}{\frac{Ne^2Et}{2\ m}} = \frac{2\ m}{Ne^2t}$$

Replacing t, the average time between impacts, by 1/w where W is the average number of impacts per second per electron we may write

$$R = \frac{2\ m\ W}{N\ e^2}$$

Or the conductivity may be similarly expressed as

$$C = \frac{N\ e^2}{2\ m\ W}$$

DRUDE'S THEORY APPLIED TO LIQUID ALLOYS

I. Alloys in which no compounds are formed.

On this basis if we assume a simple mixture of two simple metals of N and N_1 free electrons per centimeter cube, and corresponding impact frequencies W_0 and W_1 respectively, we may express the number of free electrons in the mixture as

$$N_\theta = N_0 (1 - \theta) + \theta N_1,$$

in which θ is the atomic percent of the second metal. The impact frequencies may be expressed similarly as,

$$R_\theta = \frac{2mW_\theta}{e^2 N_\theta} = \frac{2m}{e^2} \frac{W_0(1 - \theta) + W_1\theta}{N_0(1 - \theta) + N_1\theta} \quad (1)$$

This equation may be expressed in terms of the resistivity of the first metal as follows:

$$R_\theta = \frac{2m}{e^2} \frac{(W_0 - W_0\theta + W_1\theta)}{(N_0 - N_0\theta + N_1\theta)}$$

$$= \frac{2m}{e^2} \frac{W_0 - \theta (W_0 - W_1)}{N_0 - \theta (N_0 - N_1)}$$

$$= \frac{2mW_0}{e^2 N_0} \frac{1 + \theta \left(\frac{W_0 - W_1}{W_0}\right)}{1 + \theta \left(\frac{N_0 - N_1}{N_0}\right)}$$

But $\frac{2mW_0}{e^2 N_0} = R_0$, and we may write w for convenience for $\frac{W_0 - W_1}{W_0}$, and n for $\frac{N_0 - N_1}{N_0}$ for convenience and then we have,

$$R_\theta = R_0 \frac{1 + w\theta}{1 + n\theta}, \text{ in which } R_0, w, \text{ and } n, \quad (2)$$

are constants.

Moreover this equation may be shown to be a rectangular hyperbola between θ and R_θ. Writing the general form for the equation of a rectangular hyperbola using θ, and R_θ we have

$$(R_\theta + A)(\theta + B) = C^2$$

or $R_\theta\theta + R_\theta B + A\theta + AB - C^2 = 0$

dividing by B

$$1/B\ R_\theta\theta + R_\theta + A/B\theta + A - C^2/B = 0.$$

Clearing the equation (2) of fractions we have

$$R_\theta + nR_\theta - R_0 - wR_0\theta = 0.$$

These two equations are seen to be of the same form and equating the coefficients, we have

$$n = 1/B,\ -wR_\theta = A/B,\ \text{and}\ -R_0 = A - C^2/B$$

Therefore from the concentration-resistance curves of an alloy we should be able to determine w and n on finding the origin of the hyperbola and the values of the constants A, B, and C.

A straight line relationship may be had from (2) as follows:

$$(1 + n\theta)\ R_\theta = R_0\ (1 + w\theta)$$

$$R_\theta + R_\theta n\theta = R_0 + wR_0\theta$$

$$R_0 - R_\theta = R_\theta\theta n - wR_\theta\theta$$

$$\frac{R_0 - R_\theta}{\theta} = R_\theta n - R_\theta w \qquad (3)$$

This equation represents a linear relationship between $\frac{R_0 - R_\theta}{\theta}$ as one variable and R_θ as the other. The slope of the line is

$$\frac{d\left(\frac{R_0 - R_\theta}{\theta}\right)}{d\ R_\theta} = n$$

With no change in the constants w and n this relationship should hold.

The intercept of the straight line on the

$$\frac{R_0 - R_\theta}{\theta}$$

axis is $-R_\theta w$. Both w and n can therefore be found and equation (3) should be a test for the presence of a compound or any change in w or n.

If θ is expressed in percent, $\frac{R_0 - R_\theta}{\theta}$ will be one hundred times smaller. The equation will still hold, however, if w and n are correspondingly the relative change in W_θ and N_θ respectively for a change in the concentration of one percent since $R_\theta n = wR_0$ is likewise one hundred times smaller. Similarly, any other unit might have been chosen for θ and the equation still hold if w and n are the relative changes for this amount.

II. Compounds.

When a compound is formed, N_1 and W_1 may now represent the free electrons and frequency of impact of the compound. θ however, the atomic concentration of the original contents, could not represent the concentration of the compound, as usually considered. The concentration of the compound expressed in terms of the original components would depend on the number of atoms of each of the components uniting to form the new molecule.

If, however, the second component merely robbed the first, or caused it to give up more free electrons above the number found in the original components, then some abrupt change might be found at some definite concentration, and a new N_2 would appear which would be the free electrons of the second original component.

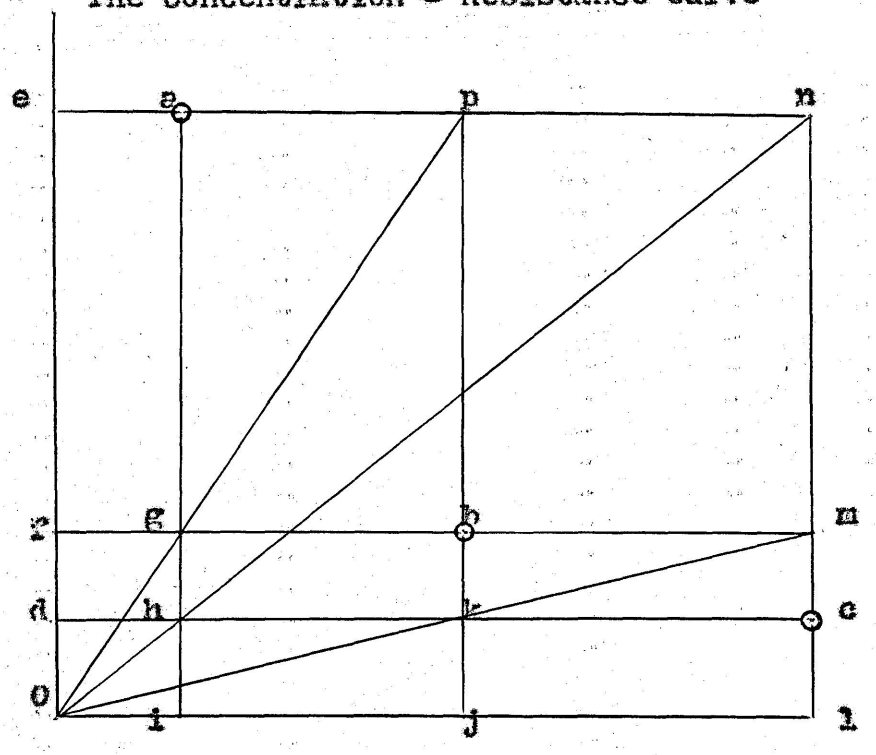
$$w_1 = \frac{W_0 - W_1}{W_0} \qquad n_1 = \frac{N_0 - N_1}{N_0}$$

$$w_2 = \frac{W_1 - W_2}{W_1} \qquad n_2 = \frac{N_1 - N_2}{N_1}$$

Thus if θ remains the atomic concentration of the original components, anything other than a simple addition of electron densities should show a change in the slope of the line represented by the equation (3).

GRAPHICAL RESULTS

The Concentration - Resistance Curve



Three points lie on a rectangular hyperbola if the diagonals of the rectangles formed on the points, sides parallel each to each and to the co-ordinates intersect at a common point called the origin.

Let a, b, and c be the points. Construct the rectangles apbg, anch, and bmck. Draw the diagonals pg and mk, and let them intersect at O. Extend ap to e and n, gb to f and m, and ck to hd, etc.

The rectangle oeai equals rectangle ofbj, for

Triangle Oep = Triangle Opj
Triangle gap = Triangle gpb
Triangle Ofg = Triangle Ogi

The diagonal of a rectangle divides it into two equal similar triangles.

Rectangle Oeai = Triangle Oep - Triangle gap
+ Triangle Ogi
Rectangle Ofbj = Triangle Opj - tri.gpb
+ tri. Ofg

But the triangles being equal as indicated before, the rectangles are also equal.

A similar proof holds for the rectangles Ofbj and Odcl. As the area of each rectangle is the product of the x and y values of the point xy = constant for each point. Moreover, the diagonal of a third rectangle, anch, may be shown to intersect at the same point O.

The rectangle Oenl is bisected by On. h is the intersection of rectangle Oeai and rectangle Odcl and lies on the diagonal On, for subtracting already proven equals OeahO from the triangle Oen, and OhclO from triangle Onl leaves equal remainders. This being the case, the line hn must bisect rectangle hanc and be its diagonal.

This test for the presence of the rectangular hyperbola was applied to the resistance - concentration curve. The graphing of the curve is shown on the plate. IV. The scale chosen was such as to make the concentration more exaggerated than the resistance as the concentration varied so slow in the first part of the curve compared to that of the resistance. All the points on the resistance - concentration curve were plotted on this graph down to twenty-five percent. The larger rectangles were first constructed using as large a variation of the points as possible in order that one point may not be repeated more than necessary. The diagonals of the rectangles were then drawn, the larger ones first as the construction is liable to contain less error. All the diagonals could be made to pass through the same point as far as it was able to observe with construction, except the last one which is the 24.26 %. In the testing with the straight line this was the first point to be off. There are two rectangles constructed with this point and they both went above the point that all the others passed through. None of the other points that follow this one satisfy the condition, so the curve follows that of the rectangular hyperbola only to the 24.26% value.

The values of dR/dO, $(= \frac{R_o - R_o}{\quad})$ are plotted against the corresponding ones of dR. All the values fall on a straight line until the value of 24.26% is reached. The points all began falling off the line as is seen from plate IV. This is the second test and is an analytical one for the showing that the curve follows a rectangular hyperbola until the value of 24.26% is reached. From this curve we may now obtain n and $R_o w$, hence w.

From 34.2 % to 74.4% the curve takes the form of a straight line as far as the experimental observation goes. From 74.4 % to 91.6 % apparently another straight line and from 91.6 % to 100 % another. These last two lines are so short that they may be parts of some other curve, but they are so nearly straight that we will assume no change in n. This means that n for these straight lines will be taken as 0. The w will change as will be shown later. From the proofs given for the hyperbola, it is clear that the n and w are constants and the curve follows the equation (2) in the resistance form until about 24.26 % Pb is reached,

$$R_\theta = R_0 \frac{1 + w\,\theta}{1 + n\,\theta}$$

On the plate III where the graphical construction of the hyperbola is shown some of the points of the straight line that follows on the curve are plotted and the line drawn through them cutting the hyperbola at some point. This is an effort to get the true or theoretical point of intersection of the two curves, for the getting of the R and W at this point. This may be obtained in three ways. It may be found from the straight line on plate IV, from a geometrical construction of the rectangles on the hyperbola, or may be obtained analytically from the equation of the hyperbola and the line. The graphical method on the hyperbola is shown. The value of the point found is at 27.5 % at R = .01600. The value of R_0 used down to this point is that of the pure mercury. From here to 100 % the value of n is 0, therefore the equation for the curve falls in the form

$$R_\theta = R_0 (1 + w\,\theta)$$

or

$$w\,\theta = R_\theta - R_0 = W_\theta,$$

where W_θ is the impact frequency taken at that concentration and R_0 is the resistance of the lowest point on the curve. W_θ is then obtained. This is when referrered to the valuW_0obtained from the former curve, or is the new zero point and to get the total W to be plotted we must add this to the last zero value. This is done throughout the curve after the n is 0.

As is seen from the curves on the plate IV, the value of n is the same for different temperatures as the curves (1) and (2) are parallel, then w is all that changes with the temperature.

The value of R_0w may be obtained in three ways, (1) from the intercept of curve 7 on the dR/dθ axis, (2) from the constants measured from the hyperbola as has been formerly discussed and (3) from the formula,

$$\frac{R_0 - R_\theta}{\theta} = n R_\theta - R_0 w,$$

all is known, as n is obtained from the curve 1, plate Iv, and w may be obtained. The actual values of θ are used and w calculated in this way for several values of θ, and the average taken. This average compared well with that obtained from using 27.5% and the value obtained from the hyperbola.

$$n = \frac{(R_0 - R_\theta)/\theta}{R_\theta} = \frac{.25}{.0094} = \underline{26.6}$$

or for 1 % N = .266

n, from hyperbola, = 26.66

For 27.5 % change in N, N_1 = 27.5 x .266 = 7.315

or N = 8.315

as the values of w and n are compared to pure mercury and taken as unity.

$R_0\theta$ = (.016 x 26.6) - .0333 = .3923

or w = .3923/.02518 = 15.59 or .1559 for 1% W.

and W for 27.5% is 27.5 x .1559 = 4.288 = 5.288 W_0.

W (from 27.5 to 74.4) = .01795 - .01600 = .001950

$$\frac{W}{W_0} = 1.950$$

Therefore $\frac{W}{W_0} = 5.288 + 1.950 = \underline{7.238}$ *

W (from 74.4 to 91.6) = .01837 - .01795 = .00042

$$\frac{W}{W_0} = .42$$

Therefore $\frac{W}{W_0} = 7.238 + .42 = 7.658$ *

W (from 91.6 to 100) = .01784 - .01837 = -.00053

$$\frac{W}{W_0} = -.53$$

Therefore $\frac{W}{W_0} = 7.658 - .53 = 7.128$ *

The slope of each of the curves on plate I is taken and the slopes plotted against the θ %. The curve formed was found by the graphical method to follow that of anrectangular hyperbola to about 25 %. Here the lines became straight or very nearly so. When the curve became straight the inaccuracy of the curve although very small was very great compared to the values sought therefrom, so that it was better to draw results from our other curves. The hyperbola shows that $\frac{dw}{dT}$ and $\frac{dR}{dT}$ are constant.

This is evident from the curves I and II on plate at T = 200 and 350°. It is seen that the lines are straight therefore there is no change in n, therefore dn = 0. From here 27.5% to 74.4%, the relation can best be seen from plotting a couple of resistance curves at different temperatures. The temperatures taken are 350 and 300°. As is seen the lines are nearly parallel indicating a very small change in n, with the temperature. The value of n is still 0 for the resistance - concentration. The same is carried to 100 % or pure lead, and n found to vary very little with the temperature.

We may conclude then, that the value of n is practically 0 for the variation in temperature and therefore there is a linear change in w with the temperature.

Conclusions:

Mercury-Lead and Lead-Tin Alloys

The resistance of mercury-lead alloys has been explored and experimentally determined from 200° to 400° C. In many cases the temperatures have been experimentally determined both above and below this pair of values. The resistance of lead-tin alloys has been determined between the temperatures 300° to 500° C, experimentally. Both alloys were investigated from 0% of one to 100 % of itself, or 0% of the other component.

The resistance at a given temperature in the form $R_\theta = R_\theta (1 + w\theta)/(1 + n\theta)$, where w and n are constants could be applied to the mercury-lead from 0 to 27.5 % but as the curve came to be formed of straight lines after this, n could be assumed 0 and the resistance at a given temperature was given by the equation in the from, $R_\theta = R_0 (1 + w\theta)$ showing that the w varied with the concentration. This equation, $R_\theta = R_0 (1 + w\theta)/(1+n\theta)$ could not be applied to any portion of the tin-lead curve; but by assuming that n is 0, as the curve consisted essentially of several straight lines at 450°, the form $R_\theta = R_0 (1 + w0)$ is applied and the values of w may be taken directly from the curve as has been shown in the discussion.

From the facts in the above we then draw the conclusion that n is independent of temperature and w varies with it linearly. The data and results are consistent with the simple electron theory of Drude, with the exception of his assumptions as to temperature. This has been found to be false some time ago in many cases.

In concluding this report the writer wishes to express his thanks to Doctor C.V.Kent for his constant interest and assistance in the work, and Doctor F.E.Kester and staff for their help in securing the necessary apparatus and supplies.

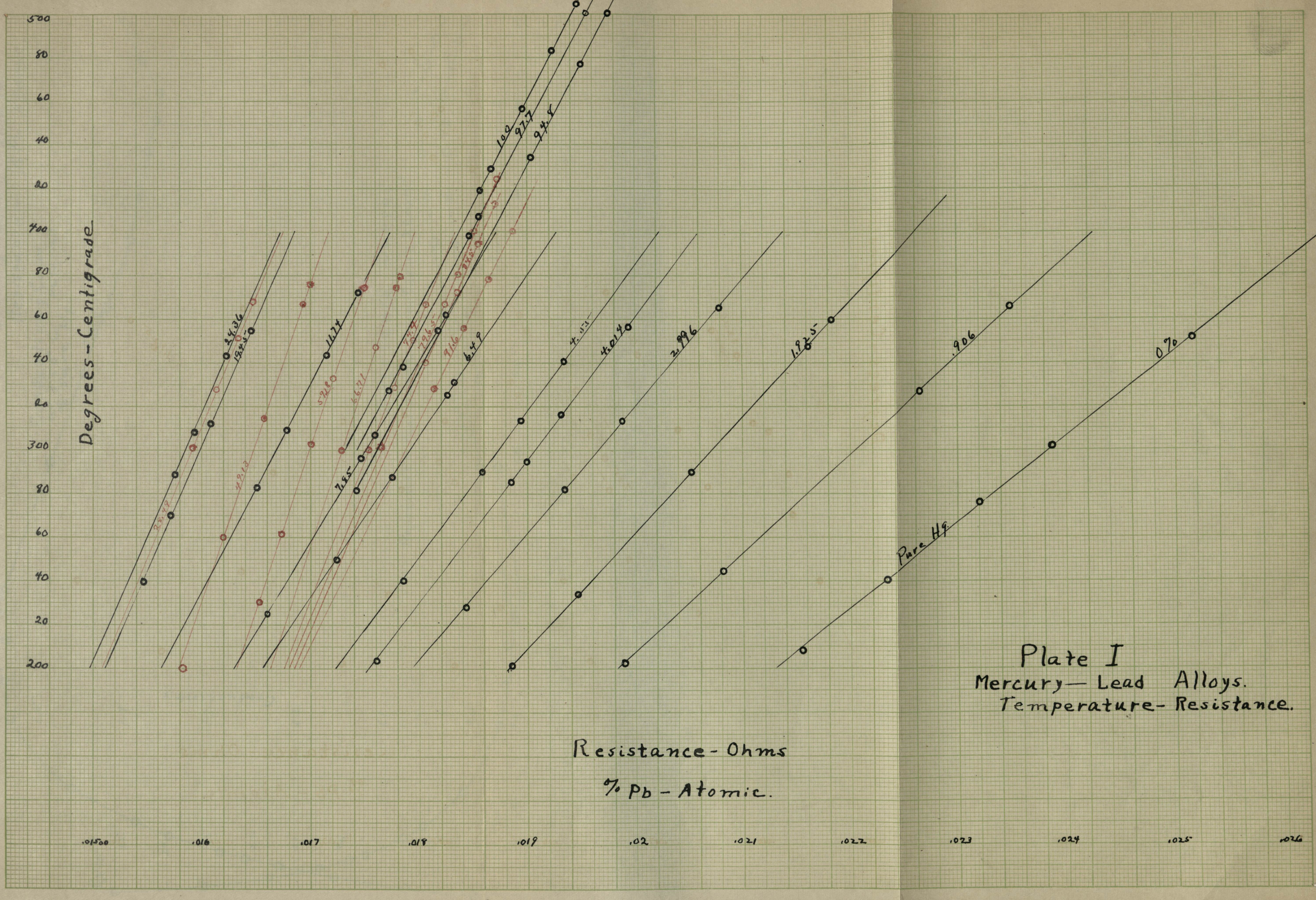


Plate I

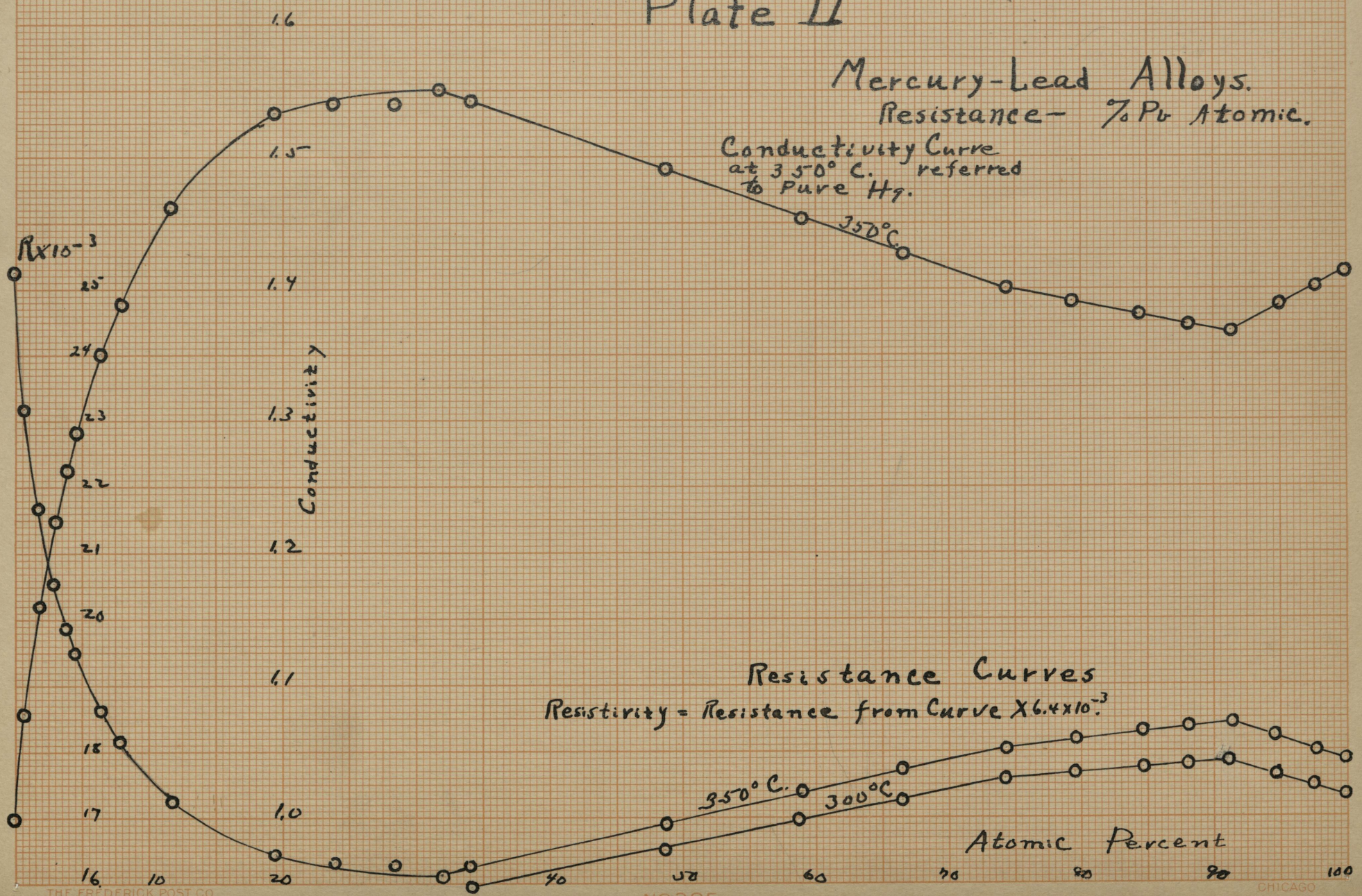
Mercury — Lead Alloys.

Temperature - Resistance.

Plate II

Mercury-Lead Alloys.

Resistance – % Pb Atomic.



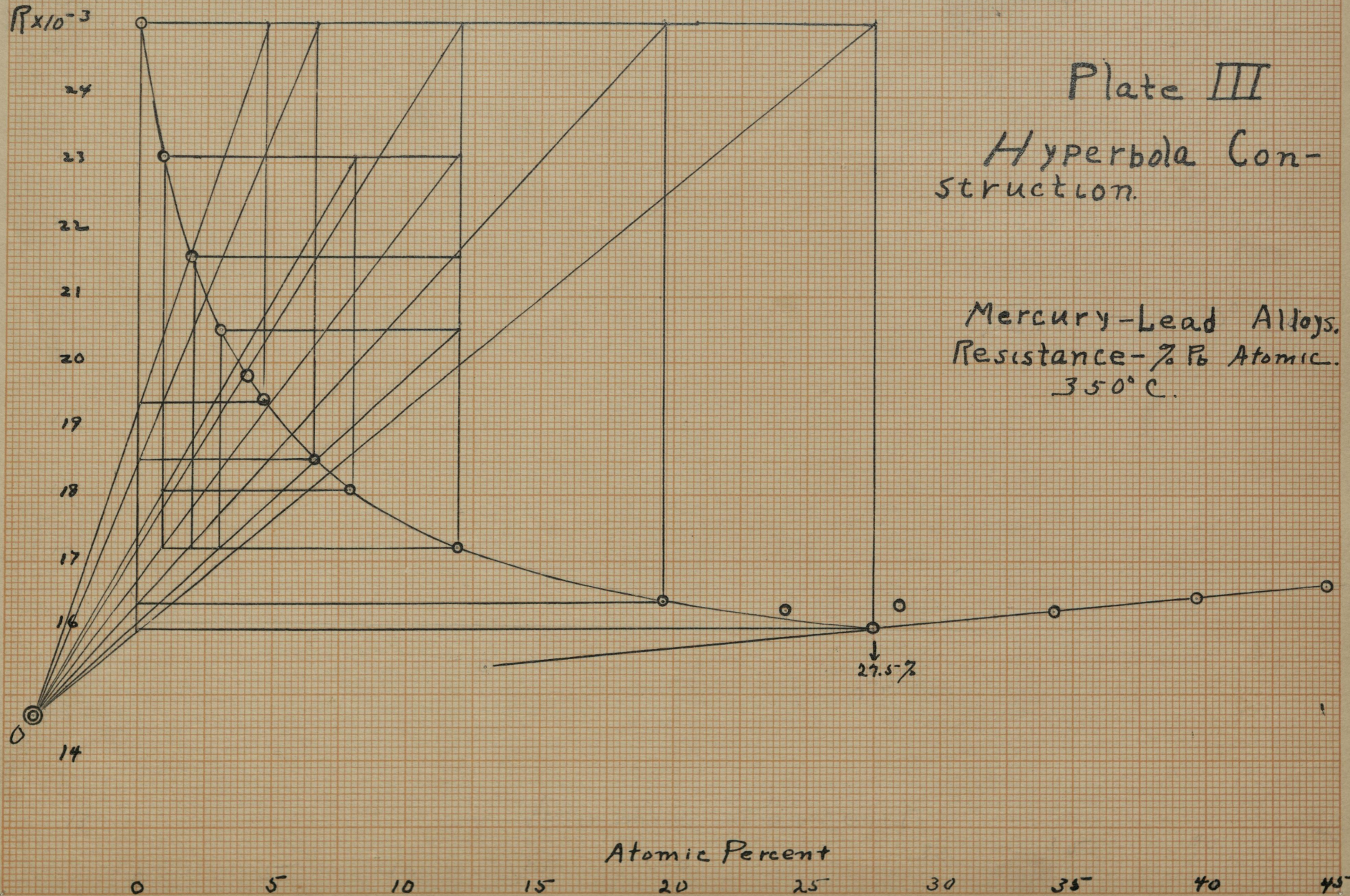


Plate III

Hyperbola Construction.

Mercury-Lead Alloys.
Resistance-% Pb Atomic.
350° C.

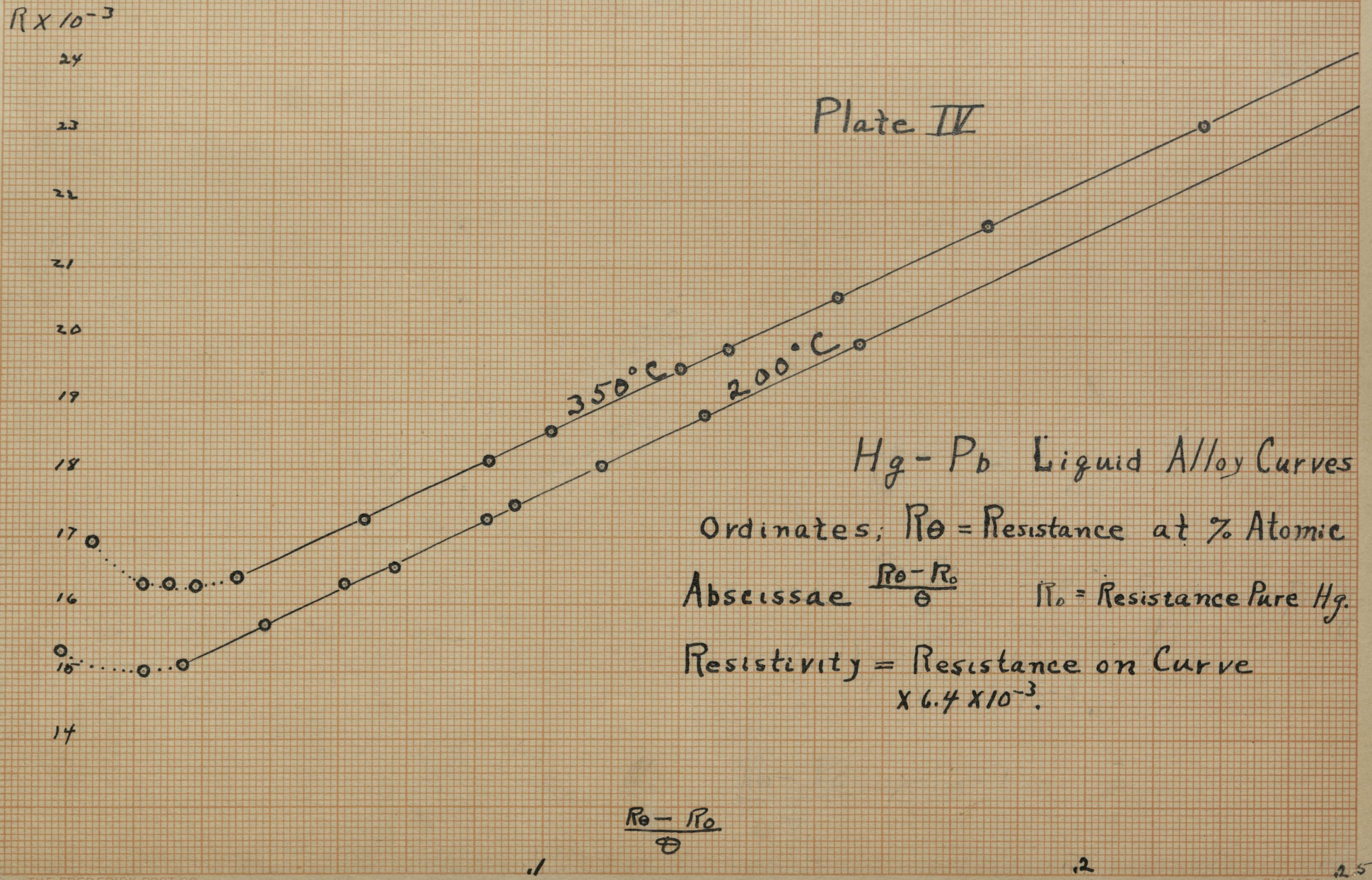
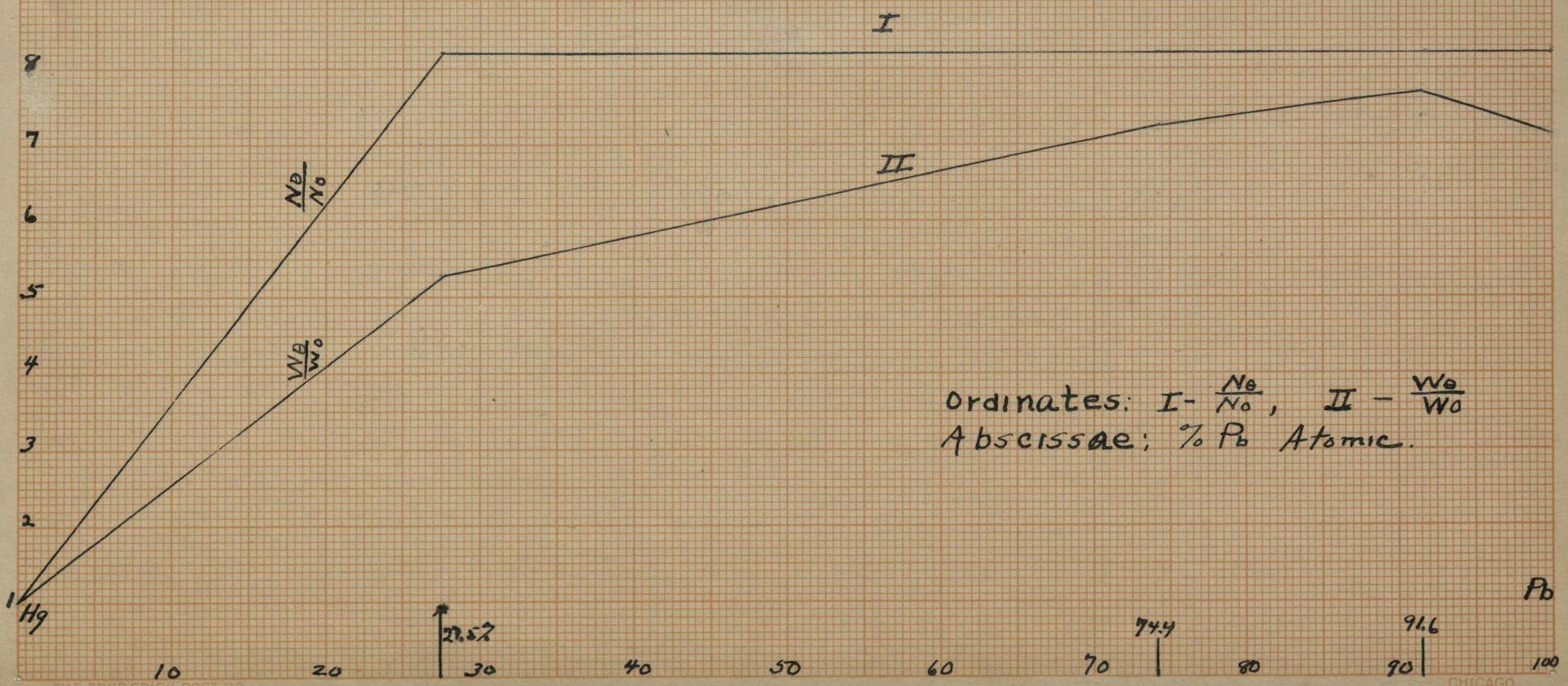


Plate V

Theoretical Changes in Electron Characteristics.



Ordinates: I- $\frac{N_\theta}{N_0}$, II - $\frac{W_\theta}{W_0}$

Abscissae; % Pb Atomic.

EXPERIMENTAL DATA

Alloy of Tin and Lead. Percent Tin in Alloy.

Composition % Tin Weight	Composition % Atomic.	Platinum Resistance Ohms	Temperature - ° C.	Bridge Alloy- Resistance
0	0.000	101.52	276.4	.009278
		107.88	312.2	.009452
		112.16	336.6	.009592
		114.46	349.7	.009658
		127.56	426.3	.010045
1	0.577	104.86	295.0	.009377
		114.16	348.1	.009656
		137.66	477.2	.010423
		133.26	460.3	.010305
		140.18	501.8	.010442
2	1.16	103.90	289.8	.009331
		108.30	314.6	.009462
		114.86	352.0	.009643
		125.54	414.4	.009933
		136.42	479.3	.012340
3	1.748	114.08	347.5	.009639
		122.16	394.2	.009881
		134.16	465.6	.010235
		141.54	510.0	.010567
		142.16	513.8	.010481
10	6.003	106.84	306.4	.009754
		116.98	359.0	.010032
		128.96	434.7	.010478
		139.16	495.6	.010851
		130.84	445.8	.010510
20	12.56	106.96	307.0	.010225
		114.54	350.4	.010459
		125.42	413.6	.010771
		138.82	493.8	.011203
30	19.76	108.18	314.9	.010773
		114.92	352.5	.010982
		125.74	415.5	.011309
		132.54	456.0	.011531
40	27.7	109.02	319.0	.011382
		113.08	342.0	.011502
		119.08	376.6	.011693
		130.98	446.5	.012112
		146.86	506.0	.012473

50	36.55	138.50	492.0	.013130
		139.70	499.0	.013170
		135.42	483.2	.013005
		123.42	402.0	.012593
		116.30	360.5	.012357
55	41.26	111.98	335.6	.012602
		123.78	404.0	.013002
		140.58	504.0	.013673
		133.44	461.3	.013387
		121.50	391.0	.012949
60	46.43	104.36	292.3	.012923
		111.90	335.0	.013202
		118.70	374.5	.013435
		134.50	467.5	.014012
		137.72	497.0	.014232
67	53.85	108.26	314.4	.013524
		115.12	353.8	.013773
		131.68	450.6	.014435
		143.96	524.8	.014943
		126.96	423.0	.014230
75	63.30	141.50	510.0	.015623
		147.32	546.0	.058520
		136.80	481.4	.015436
		122.40	396.0	.014883
		116.00	359.0	.014622
80	69.70	117.80	369.0	.015273
		124.50	408.0	.015542
		135.20	471.2	.015985
		149.13	542.4	.016463
85	76.49	117.12	365.2	.015915
		128.20	430.0	.016373
		136.00	476.6	.016734
		143.64	523.0	.017053
90	83.75	118.02	382.00	.016678
		134.18	465.8	.017395
		141.90	512.0	..017752
		146.60	541.0	.017963
95	91.60	135.84	475.4	.018352
		138.25	490.2	.018493
		120.46	379.0	.017482
		128.12	424.3	.017895
		142.30	514.6	.018633
100	100.00	126.28	418.8	.018621
		132.68	456.6	.018962
		136.88	482.8	.019271
		140.52	504.2	.019470
		127.98	428.8	.018760
		146.34	539.6	.019823

Resistance of the Tin-Lead Alloy
At 350° C and 550° C

Composition % Pound Weight.	% Pound - Atomic	R_{350} x 10^{-3}	R_{550} x 10^{-3}
0	0.000	9.64	10.74
1	0.577	9.65	
2	1.160	9.66	
3	1.748	9.67	
10	6.003	9.98	11.10
20	12.560	10.44	11.50
30	19.760	10.96	12.04
40	27.700	11.57	12.74
50	36.550	12.34	13.42
55	41.260	12.69	13.95
60	46.430	13.28	14.54
67	53.850	13.76	15.11
75	63.300	14.59	15.90
80	69.700	15.15	16.51
85	76.490	15.79	17.26
90	83.750	16.44	18.06
95	91.600	17.23	19.00
100	100.000	17.94	19.86

THE ALLOY OF LEAD-TIN

This alloy was investigated with the same apparatus and methods as the mercury-lead. The alloy was started at the pure tin and percents of lead were added until the one hundred percent lead was reached. This alloy was somewhat easier to work than the former one in that higher temperatures could be used giving a larger temperature range and hence more points for the curves. The temperature-resistance curves were obtained which were straight lines and plotted as before. The curves all went in the same direction, that is, the resistance increased with the addition of lead and the highest resistance was reached with the pure lead.

The resistances were read from the curves for the temperatures of 350° and 550°C. These were plotted on a resistance-concentration scale both for the percent lead by weight and percent atomic. The resistance by weight curve gave a sagging curve. When the resistance was plotted against the atomic percent we got a curve that seemed to be broken into four lines which could be taken on the 350° curve to be straight if we neglected the one point at 46.43 percent. This point repeats itself and shows up more plainly in the higher temperature curve. With low concentrations of lead, it is seen that the curve runs horizontal to about three percent where it breaks and rises at an angle. If the curve consists of straight lines, n would be 0 as has been shown before and we would have the form of an equation the same as before:-

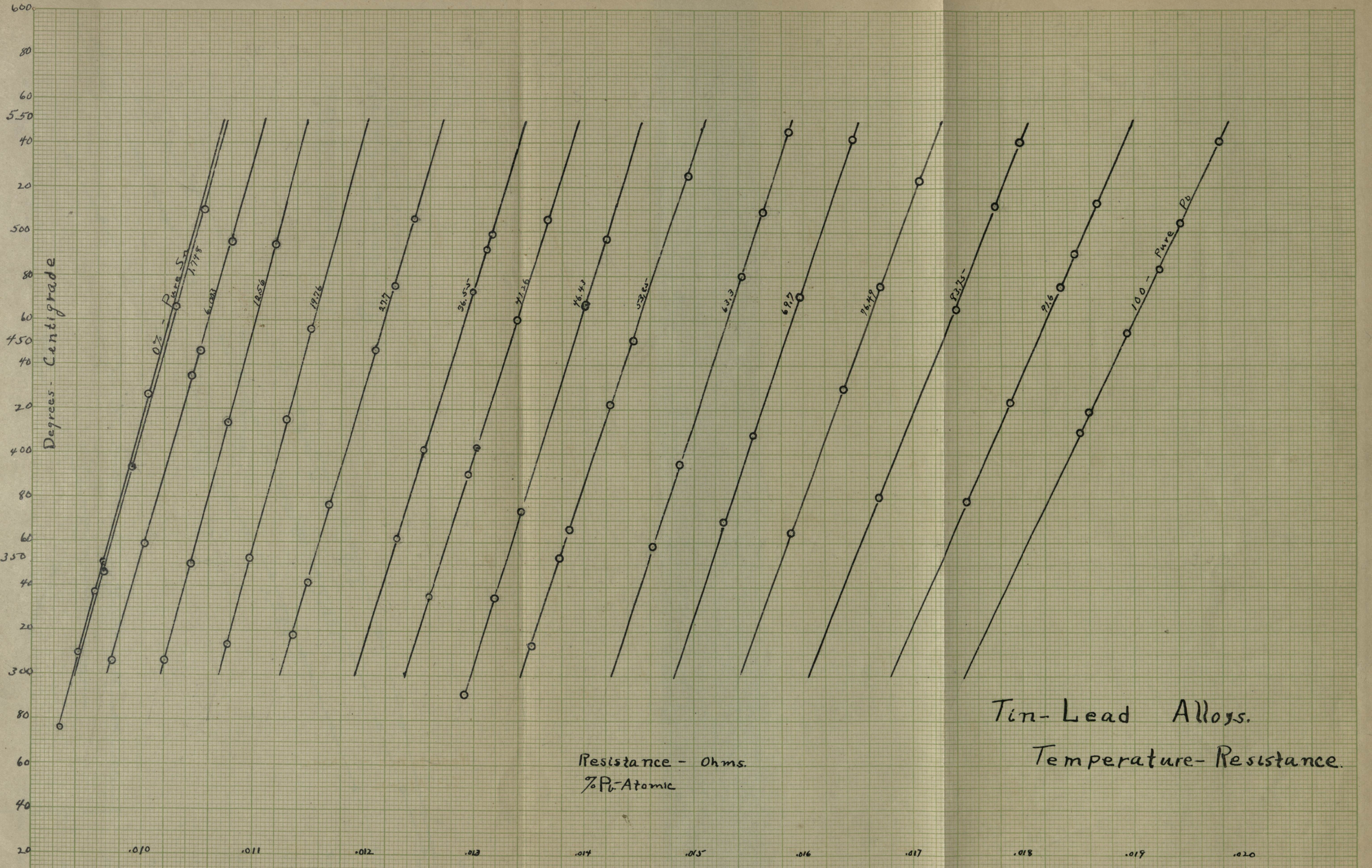
$$R_\theta = R_0 (1 + w\theta)$$

or $$w\theta = R_\theta - R_0 = W_\theta$$

where W_θ is the frequency impact referred to the zero point which is the first point on the line or the last one considered on the last. It is seen that the value of W may be read directly from the Rθ curve for 350° C if considered as straight lines, as may be done, for they are so nearly straight that n is very small, and would be negligible compared to the accuracy of the curve. Since the curve for this alloy falls into this form, we have no use for the tests that are used on the former alloy, and hence it is not in the same family as the other. The tests applied are more suitable for curves of large curvature.

Since the point mentioned repeats itself experimentally and is further verified by neighboring

points at higher temperatures it must have some significance. The melting point curve taken from Physicalisch-Chemische Tabellen is drawn on the plate with the Pb-Sn curves. There seems to be no close relation between the breaks in the melting point curve and the resistance curve.



Tin-Lead Alloys.

Temperature-Resistance.